

Barwood, M. J., Goodall, S., & Bateman, J. (2018). The effect of hot and cold drinks on thermoregulation, perception, and performance: the role of the gut in thermoreception. European journal of applied physiology, 1-12. https://doi.org/10.1007/s00421-018-3987-8

# The effect of hot and cold drinks on thermoregulation, perception and performance: the role of the gut in thermoreception

Martin J Barwood[1*], Stuart Goodall[2], Jon Bateman[2]

[1]Department of Sport, Health and Nutrition, Leeds Trinity University, Horsforth, Leeds U.K.

[2]Northumbria University, Department of Sport, Exercise and Rehabilitation, Northumberland Road, Newcastle Upon Tyne, U.K.

Running head: Hot and cold drinks

This work was funded by a research grant from the European Hydration Institute

There are no conflicts of interest to declare

*Corresponding Author: Dr Martin Barwood, Dept. Sport, Health and Nutrition, Leeds Trinity University, Brownberrie Lane, Horsforth, LS18 5HD, UK. Tel: +44 (0) 113 283 7100.

Email. m.barwood@leedstrinity.ac.uk

## Abstract

**Purpose.** Hot compared to cold drinks alter sweating responses during very low intensity exercise in temperate conditions. The thermoregulatory, perceptual and performance effects of hot compared to cold drinks in hot, dry conditions during high-intensity exercise have not been examined. **Method.** Ten participants (mean ± SD characteristics age 25 ± 5 years, height 1.81 ± 0.07 m, body mass 73.5 ± 10.6 kg, maximal power output ($P_{Max}$) 350 ± 41 W). completed two conditions where they drank four boluses (ingested at -9, 15, 30 & 45 minutes respectively) of 3.2 $mL.kg^{-1}$ (~960 mL total) of either a COLD (5.3°C) or a HOT drink (49.0°C), which were contrasted to a no drink CONTROL. They cycled for 60-minutes (55% $P_{Max}$ in hot (34.4°C) dry (34% RH) ambient conditions followed by a test to exhaustion (TTE; 80% $P_{Max}$). The thermoregulatory, performance and perceptual implications of drink temperature were measured. **Results.** TTE was worse in the CONTROL (170 ± 132 s) than the COLD drink (371 ± 272 s; p = .021) and HOT drink conditions (367 ± 301 s; p = .038) which were not different (p = .965). Sweat responses (i.e. reflex changes in mean skin temperature ($T_{msk}$) and galvanic skin conductance) indicated transient reductions in sweating response after COLD drink ingestion. The COLD drink improved thermal comfort beyond the transient changes in sweating. **Conclusion.** Only COLD drink ingestion changed thermoregulation but improved perceptual response. Accordingly, we conclude a role for gut thermoreception in thermal perception during exercise in hot, dry conditions.



**Keywords:** cold drinks, gut thermoreception, hot drinks, thermal comfort.

## List of Abbreviations

Analysis of variance (ANOVA)

American College of Sports Medicine (ACSM)

Fixed intensity (FI)

Galvanic skin conductance (GSC)

Gut comfort (GC)

Heart rate (HR)

Maximal power output ($P_{Max}$)

Mean skin temperature ($T_{msk}$)

Rating of perceived exertion (RPE)

Rectal temperature ($T_{rec}$)

Relative humidity (RH)

Skin wetness (SkW)

Standard deviation (SD)

Test to exhaustion (TTE)

Thermal comfort (TC)

Thermal sensation (TS)

Wet bulb, globe, temperature (WBGT)

## Introduction

Exercise performance and physical activity capacity are limited by dehydration (Rowell et al. 1974). Dehydration is exacerbated by increases in environmental temperature because of high sweat rates in order to control the rise in deep body temperature (Rowell et al. 1966). This problem applies to those undertaking extended exercise in both competitive and recreational scenarios. It is generally accepted that modest dehydration of approximately 2% is sufficient to reduce maximal aerobic exercise performance and increase the cardiovascular demand of sub-maximal exercise (ACSM et al. 2007). Consequently it is advisable to maintain hydration status within these limits. There is much on-going debate on the best practise for maintaining hydration status in such circumstances which include *ad libitum* drinking (Armstrong et al. 2014), thirst driven fluid consumption (Hew-Butler et al. 2006) and fluid consumption per kilogram of body mass (Noakes, 2011). The ACSM guidelines suggest drinking fluids of between 15°C and 22°C, at a rate of 0.4-0.8 $L.hr^{-1}$ in temperate conditions and to avoid body mass loss of greater than 2% irrespective of ambient conditions (ACSM et al. 2007). Such guidance is of critical importance particularly during exercise in hot conditions where, if adequate fluid is not ingested to balance sweat losses, deep body temperature may increase disproportionately (hyperthermia), culminating in heat related illness and ultimately circulatory and physical collapse (Rowell et al. 1966).

To date the temperature of ingested fluid has primarily been considered on the basis of palatability (e.g. ACSM et al. 2007). However, there is evidence that hot (i.e. 50°C) compared to cold drinks (i.e. 10°C, 4.5°C) could change body temperature regulation and sweat rates during physical activity and possibly sports performance (Bain et al. 2012; Lee et al. 2008). Continued exercise is liable to arouse a thirst response and the vast majority of

people would choose a cool drink to lessen their thermal discomfort from both a physiological and perceptual viewpoint (Barwood, 2012). This selection probably occurs because of the greater hedonic tone of cold drinks (Szylk et al. 1989). Yet, Bain et al. (2012) have suggested that ingestion of hot fluids (50°C) probably *reduced* body heat storage when compared to cold (1.5°C) and cool (10°C) drinks because of a disproportionate influence upon sweat rate by stimulation of a gut thermoreceptor. Specifically, hot fluid ingestion increased sweat production and rate beyond the thermal mass of the fluid itself but this was not evident with a cold drink; although the validity of the resultant net change in body heat storage has recently been challenged (Lamarche et al. 2015). These findings have important implications for fluid replacement guidelines. Theoretically, in certain circumstances the consequence of hot fluid ingestion may be to *reduce* the risk of heat illness by increasing sweating assuming adequate fluid is available to balance the extra sweat. The studies of Bain and colleagues (2012) along with Morris and colleagues (2014) are applicable to low work rates where the evaporation capacity of the environment was high (i.e. low ambient temperature and humidity; 23.6°C/23.7°C & 11%/32% RH). These data, coupled with studies performed at rest (e.g. Nadel et al. 1970), show that the thermoregulatory responses are influenced by drink temperature but the picture at higher work rates, in relation to performance and at higher ambient temperatures is less clear.

Studies that have been performed at higher ambient temperatures humidities and higher exercise work rates (e.g. Lee & Shirreffs, 2007; Lee et al. 2008a & b; Burdon et al. 2008; Mundel et al. 2006) have not reached a consensus on the effect on sweating but do suggest a possible performance improvement when cold fluid is ingested in a hot or temperate environment (Burdon et al. 2010). Accordingly, it is important to consider both the perceptual and biophysical (i.e. heat exchange) consequences of different temperature drinks. From the

perspective of thermal perception, the sensation of a hot drink stimulating the gut may actually increase thermal discomfort and consequently reduce exercise capacity and performance. This would contrast the hypothesised benefit of increasing sweat production that would occur. This places the behavioural (i.e. thermal discomfort is a profound behavioural driver; Taylor et al. 1995) and biophysical mechanisms that may influence physical performance in direct conflict.

Many of those studies that have examined the performance effect of different temperature drinks have not directly measured regional sweat responses and have instead used a surrogate of regional sweating performance in the form of lowered skin temperature. This is despite well-known discrepancies between regional sweat rates and blood flow thereby producing different drivers of regional skin temperature (Smith et al. 2013; Smith & Johnson, 2016). Similarly, unrealistic drinking protocols that use large volumes of fluid (e.g. Lee et al. 2008b) and/or that include temperature response priming by consumption of large boluses of fluid in advance of exercise (e.g. Lee & Shirreffs, 2007) with extended periods of seated rest, all contribute to the confusion over any performance and thermoregulatory effect. Importantly, these studies raise the possibility thermal effects but do not reflect the real world scenario where preparatory periods before exercise may be short. Likewise, flavoured beverages have also been used which may increase drink consumption, frequency and hedonic tone when the primary variable of interest is drink temperature (e.g. Mundel et al. 2006). Lastly, it is prudent to ensure only the gut thermoreceptors are targeted by a given temperature drink and care must be taken to protect the skin (palm) from cooling and warming prior to beverage consumption. This is especially prudent given the density of thermoreceptors on the hand that may subsequently drive thermal comfort (Hensel, 1984).

Accordingly, this study aims to examine whether the ingestion of a hot drink (i.e. 50°C) is beneficial to thermoregulation at rest and during exercise in hot conditions when evaporation is enabled (i.e. a dry environment) when contrasted to a cold drink (i.e. 5°C) and a no-drink control. We hypothesised that hot fluid ingestion would accelerate the onset of sweating and increase sweat production thereby lowering skin temperature and cardiovascular strain ($H_1$). Secondly, a hot drink would increase gut discomfort and alter thermal perception ($H_2$). Finally, performance may be influenced by the resultant effects of drink temperature with cold drinks having an ergogenic effect ($H_3$).

## Methods

### *Participants*

The study was approved by the University ethics committee. All participants gave written, informed consent to take part. An *a priori* power analysis to see differences in TTE performance indicated nine participants were required to see a moderate effect size (0.5) at an 80% statistical power to an alpha level of 0.05 (GPower, version 3.1, Heinrich Heine, University of Dusseldorf). Twelve non heat acclimatised male volunteers were recruited to allow for participant attrition. They were trained cyclists who were accustomed to maximal exercise and undertook cycling training > 3 times per week. Their mean ± SD physical characteristics were age 25 ± 5 years, height 1.81 ± 0.07 m, body mass 73.5 ± 10.6 kg, body surface area (Dubois & Dubois, 1915) 1.93 ± 0.2 $m^2$, maximal power output ($P_{Max}$) 350 ± 41 W. Prior to each visit, participants were asked to maintain a similar diet, and to refrain from alcohol or caffeine consumption 24 hours prior. Participants arrived for each test in a hydrated state (i.e. having consumed 500 mL of water within the previous two hours).

### *Experimental design*

The participants visited the experimental facility on four separate occasions. Visit one was to undertake a preliminary $P_{Max}$ cycling test used to verify the training status and to establish the sub-maximal fixed intensity (FI) threshold for the remaining three visits. They then completed an exercise test in hot, dry conditions (35°C and 30% relative humidity [RH]) during which they consumed either HOT (50°C) or COLD (5°C) fluid or a no fluid CONTROL. The order of the test conditions was randomised using a Latin square.

*Procedure*

*Preliminary Measurements*

Participants arrived at the laboratory and changed into their cycling kit (typically anklet socks, jersey, bib shorts and cycling shoes) before height (m) and mass (kg) were measured using calibrated weighing scales (Seca, Model 705 2321009, Vogel and Halke, Hamburg, Germany) and a stadiometer (Holtain LtD, Crymych, Dyfed), respectively. Participants then entered the laboratory and mounted a stationary cycle ergometer (Velotron Racermate, Seattle, USA) and adjusted the cycling position to suit; bike position was replicated in subsequent tests for each. Participants completed a standardised warm-up before commencing the $P_{Max}$ protocol in temperate conditions (20°C, 40% RH). The participant commenced cycling at 150 W at 90 revs·min$^{-1}$. Step increases of 25 W·min$^{-1}$ were added until volitional exhaustion was reached or if participants were unable maintain a cadence within 10 revs·min$^{-1}$. $P_{Max}$ was established objectively as the highest sustained power output for a minimum of 15 s.

*Main Experimental Trials*

On arrival at the Environmental Physiology laboratory (TIS Services, Hampshire, UK) the participants were initially weighed naked (within a private room) and clothed (i.e. wearing cycling kit) for subsequent estimation of sweat production and evaporation when coupled with post-test weight measurements and fluid consumed. Participants then, in private, self-inserted after instruction, a calibrated and sterilised rectal thermistor ($T_{rec}$) 15 cm beyond the anal sphincter to measure deep body temperature during exercise. Participants were then instrumented with skin thermistors, secured by micropore tape (Transpore, 3M, London, Ontario, Canada), on the left hand side of the body at eight different body sites to enable the

estimation of mean skin temperature ($T_{msk}$; Olesen, 1980); chest, scapula, bicep, hand, thigh, hamstring, calf, and foot. They also donned a heart rate monitor (Polar FT1, Polar Electro Oy, Kempele, Finland) before entering the environmental chamber.

Participants mounted the stationary cycle ergometer after which galvanic skin conductance (GSC) sensors were attached to the bicep and subscapular region. These were used to estimate sweating onset and rate (see measurements section). The participant sat at rest on the ergometer for 10-minutes. Depending on the trial condition, the participant either ingested a hot or cold drink after 1-minute of rest or did not receive any fluid (CONTROL). Further drinks were ingested after 15, 30 and 45 minutes of exercise. Prior to each drink ingestion point (including the corresponding point in the CONTROL condition) an absorbent pad of fixed surface area was secured, using micropore tape, to the forearm and subscapular to establish regional sweat volume and rate. The pad was removed after 5-minutes. On commencement of this rest period and before and after drink ingestion point, participants reported their subjective sensations of thermal perception (comfort and sensation), perceived exertion (exercise only), skin wetness and gut comfort. Following the rest period participants commenced FI exercise at 55% of $P_{Max}$ which corresponded to 193 ± 23 W. A fan (Wahl, Model ZX220, Wahl, Sterling, IL, USA) was switched on at the start of exercise and provided a consistent wind speed of 2 to 2.5 $m.s^{-1}$ throughout the trial; wind speed was verified by an anemometer (LM-8000 Anemometer, Digital Instruments, New York, USA).

After 60-minutes of FI cycling the power output was increased to 80% of $P_{Max}$ and participants were instructed to maintain this intensity for as long as possible until exhaustion occurred; this comprised the performance based test to exhaustion (TTE) phase of the trial.

Test duration, power output, pedal cadence and heart rate were displayed throughout the FI period but were obscured during the TTE. Participants were withdrawn if their deep body temperature exceeded 40°C. Upon completion of the trial the participants exited the environmental chamber and were re-weighed.

*Drink Temperature Manipulation*

Participants ingested a fixed fluid volume of 3.2 $mL.kg^{-1}$ of body mass. This corresponded to approximately 240 mL per bolus for a 75 kg individual and a total of ~960 mL in the HOT and COLD drink conditions. The temperature of the HOT drink was established by immersing two drinks bottles in to a temperature controlled water bath (Grant Instruments (Cambridge) LtD, Shepreth, U.K) set to 50°C. In order to verify the drink temperature a thermistor was taped to the wall of the water bath and a second thermistor was immersed in to one of the drinks bottles, which was not consumed during the trial to avoid biological contamination. Temperature data were displayed on a data logger (Squirrel 1000 Series, Grant Instruments (Cambridge) LtD, Shepreth, U.K). It was assumed that the temperature established in one drink corresponded to that achieved in the one that was consumed; this method was verified in pilot studies. Immediately before drink consumption and in order to achieve an accurate drink volume, the water was poured in to an insulated plastic beaker on a weighing scale (Coline, KG-1005, Clas Ohlson, Dalarna, Sweden). To avoid warming the skin of the palm and thereby confounding thermal perception subjective reports, the surface of the beaker was insulated against temperature change. The participants were encouraged to ingest the drink as quickly as possible to avoid substantial beverage temperature changes.

The temperature of the COLD drink was controlled via an ice bath kept in a thermoneutral cupboard adjacent to the environmental chamber. A similar procedure to that described above was used to verify the drink temperature but the beaker from which the drink was consumed was also stored in the ice; the beaker insulator remained in the environmental chamber. Thereafter the same procedure as in the HOT drinks trial was used to enable accurate drink volume.

*Measurements*

*Skin Temperature, Deep Body Temperature and Environmental Temperature*

Skin temperature ($T_{sk}$; EUS-UU-VL- 2-0, Grant Instruments (Cambridge) LtD, Shepreth, U.K) and deep body temperature ($T_{rec}$ ; REC-UU-VL- 2-0, Grant Instruments (Cambridge) LtD, Shepreth, U.K) were measured by a data logger (Squirrel 2020 series, Grant Instruments (Cambridge) Ltd, Shepreth, U.K) in 10 s epochs throughout the heat exposure. Between participants, each skin thermistor was cleaned with an alcohol swab. Between participants the rectal thermistor was sterilised using medical disinfectant (Virkon, Day-Impex LtD, Colchester, U.K). The environmental conditions were measured at the mid-point of the fork of the Velotron bike using a WBGT weather station (Edale Instruments, Longstanton, Cambridge, U.K).

*Galvanic Skin Conductance (GSC)*

GSC was used to estimate sweating onset and rate of sweat gland activation; an extension of its application to sweat ion reabsorption (Amano et al. 2016). Prior to trial commencement two GSC probes (GSR MLA0118-DC-12A, AD Instruments, Castle Hill, Australia) were attached in a standardised array using micropore tape (Transpore, 3M, London, Ontario,

Canada) and a standardised amount of conductive electrode paste (MLA1095, AD Instruments, Castle Hill, Australia). The probes were integrated with a biological amplifier (FE116 GSR Amp, AD Instruments, Castle Hill, Australia). Before commencing data collection the probes were biologically zeroed whilst attached to the participant's skin. Data were collected using an analogue to digital converting system (Powerlab, 16/30 AD Instruments, Castle Hill, Australia) at a resolution of 60 Hz and subsequently averaged to 10 s epochs.

*Absorbent Pad Sweat Measurement*

Local sweat volume was established at the subscapular and forearm using a technical absorbent pad (2204CW1, Technical Absorbents LtD, Grimsby, U.K) collection technique. In accordance with the methods of Morris et al. (2013), a pad of fixed surface area (64 $cm^2$) was attached to the skin. The patch consisted of an outer area and an inner area (49 $cm^2$;) from which the volume of sweat was collected and established using high-resolution scales (OHAUS TS400D, precision balance, Florham Park, New Jersey, USA). The outer border of the pad was used to avoid sweat tracking from an unmeasured area of the skin. Between measurements of pad weight the pad was stored in an airtight Ziploc bag thereby preventing sweat evaporation. The patches were assembled two minutes prior to application and applied to the skin twenty seconds prior to each time point (i.e. −10, 15, 30 and 45 minutes; i.e. corresponding to immediately before drink consumption). This technique correlates well with ventilated sweat capsule estimates of regional sweat production (Morris et al. 2013).

*Perceptual Responses*

Participants underwent a standardized explanation of each perceptual scale before commencing the exercise trials of the following scales:

RPE was measured on a 15-point likert scale (Borg, 1982). Whole body thermal perceptions were measured using a 20 cm visual analogues scale for thermal sensation (TS) which ranges from *Very hot* (20 cm); *Hot* (17.5 cm), *Warm* (15.0 cm), *Slightly warm* 12.5 cm), *Neutral* (10 cm), *Slightly cool* (7.5 cm), *Cold* (2.5 cm), *Very cold* (0 cm). The thermal comfort (TC) scale ranges from: *Very comfortable* (20 cm), *Comfortable* (16 cm), *Just comfortable* (12 cm), *Just uncomfortable* (10.5 cm), *Uncomfortable* (4 cm), *Very uncomfortable* (0 cm). On both thermal perceptual scales the worded descriptions were used as a guide only (Zhang, 2003).

Gut Comfort (GC; adapted from Gonzalez et al. 2015) was assessed using a five point likert scale to describe digestive sensations in the stomach where 1 = *Very comfortable*, 3 = *Average comfort* and 5 = *Very uncomfortable*. Skin wetness (SkW; adapted from Storaas and Bakkevig, 1996) was used to measure the sensation of sweat accumulation on the skin using an eight point categorical scale where 1 = *More dry than normal*, 4 = *Chest and back* are wet, and 8 = *Sweat/water runs off many places*.

*Statistical Analysis*

Two of the twelve participants recruited did not complete all of the main exercise trials; data are presented for n = 10. Mean ± SD were calculated for each condition for drink temperature and volume (COLD and HOT drink trials only). Drink volume was compared between conditions (i.e. COLD drink vs HOT drink) using an independent samples t-test.

Mean ± SD were calculated for all thermal ($T_{msk}$, $T_{rec}$, and HR) and perceptual (RPE, TS, TC, GC and SkW) variables at nine different time points across the trial (trial start, pre and post each drink ingestion [6 points], end of FI exercise and TTE end); RPE was only analysed for eight time points as it was not collected at rest. The difference in sweat pad mass before and following drink ingestion was calculated. Data were compared within participant, across time and between condition (CONTROL, COLD and HOT drinks) using repeated measures analyses of variance (ANOVA). To establish the presence of any reflex changes in thermoregulatory response after drink ingestion the change in $T_{msk}$ and $T_{rec}$ were calculated for the 3-minutes following drink ingestion (due to the potential for decay in intragastric temperature 5-minutes after drink ingestion; Shi et al. 2000) and averaged across drink time points. Mean GSC was established at each measurement site (i.e. bicep and subscapular). Total sweat production, sweat evaporation, TTE duration, mean GSC, reflex change in $T_{msk}$, $T_{rec}$ were compared between condition using a one way ANOVA. *Post-hoc* pairwise comparisons were conducted to establish the direction of any significant main and interaction effects with *Bonferroni* adjustment. Estimates of effect size are reported using partial eta squared ($\eta p^2$). Confidence intervals at the 95% level data are reported for TTE data. Statistical analyses were carried out using SPSS v22 (IBM SPSS statistics, Chicago, IL, USA) to an alpha level of 0.05.

## Results

*Environmental Conditions*

Environmental conditions across trials were: dry bulb temperature 34.4 ± 0.7°C, wet bulb temperature 21.7 ± 0.9°C equating to a relative humidity of 33.9 ± 1.4%. Wind speed within the trials averaged 2.8 ± 0.3 $m.s^{-1}$.

*Performance Data*

*Time to exhaustion*

TTE performance averaged, 170 ± 132 s, 371 ± 272 s, and 367 ± 301 s in the CONTROL, COLD and HOT drink conditions, respectively. Participants exercised for significantly less time in the CONTROL condition (main effect for condition: $F_{(2,18)} = 4.287$, $p = .030$, $\eta p^2 = .323$) compared to both the COLD ($p = .021$) and HOT ($p = .038$) conditions, which did not differ ($p = .965$). 95% CI for TTE in the CONTROL, COLD and HOT DRINK trials was 76 to 265 s, 176 to 565 s, and 151 to 583 s respectively.

*Drink Volume and Temperature*

Drink volume in the HOT and COLD drink trials averaged 971 ± 171 mL and 930 ± 126 mL, respectively. Consequently, the drink volume between the HOT and COLD drink conditions was not different ($t = 1.035$ $p = .328$). Drink temperature averaged 49.0 ± 1.9°C and 5.3 ± 1.7°C in the HOT and COLD drink trials respectively.

293 *Rectal temperature ($T_{rec}$)*

294 Rectal temperature response is displayed in figure 1A. Rectal temperature increased steadily
295 during FI exercise and averaged 38.7 ± 0.6°C (grand mean ± SD) by the end of this part of
296 the protocol (main effect for time, $F_{(8,72)}$ = 43.628, p = .001, $\eta p^2$ = .829). Terminal rectal
297 temperature after the TTE indicated the participants were hyperthermic (grand mean 39.0 ±
298 0.6°C). $T_{rec}$ was higher, on average, in the CONTROL trial (main effect for condition $F_{(2,18)}$ =
299 5.436, p = .014, $\eta p^2$ = .377) than both the COLD drink (p = .019) and HOT drink trial (p =
300 .008) which were not different (p = .482). This main effect for condition did not culminate in
301 an interaction effect ($F_{(16,144)}$ = .780, p = .706, $\eta p^2$ = .080). The extent of $T_{rec}$ change in the 3-
302 minutes following drink ingestion was similar in each condition ($F_{(2,18)}$ = 1.492, p =.251, $\eta p^2$
303 = .142) and averaged 0.06 ± 0.02°C, 0.05 ± 0.02°C and 0.05 ± 0.02°C in the CONTROL,
304 COLD and HOT drink conditions, respectively.

305

306 ***INSERT FIGURE 1 NEAR HERE***

307

308 *Mean skin temperature ($T_{msk}$)*

309 $T_{msk}$ response is displayed in figure 1B. As the trial ensued the $T_{msk}$ increased but then
310 plateaued (main effect for time: $F_{(8,72)}$ = 3.982, p = .045, $\eta p^2$ = .307). This did not happen to
311 any greater extent in any of the test conditions (no main effect for condition: $F_{(2,18)}$ = 1.416, p
312 = .269, $\eta p^2$ = .136 or interaction effect: $F_{(16,144)}$ = 0.775, p = .711, $\eta p^2$ = .079). The change in
313 $T_{msk}$ following drink ingestion was significantly different in the 3-minutes following drink
314 ingestion ($F_{(2,18)}$ = 3.533, p = .05, $\eta p^2$ = .282) with $T_{msk}$ remaining unchanged in the COLD
315 drink trial (0.00 ± 0.10°C) compared to the CONTROL condition which increased (0.10 ±
316 0.10°C; p = .020), but was not different to the HOT drink condition (0.06 ± 0.10°C; p = .

200). The CONTROL condition and the HOT drink condition were not different ($p = .273$). Terminal $T_{rec}$ and $T_{msk}$ at the end of each stage of the protocol (i.e. rest, 55%, 80% $P_{Max}$) are displayed in table 1.

***INSERT TABLE 1 NEAR HERE***

*Sweat Responses*

*Whole body Sweat Estimation*

Sweat production in the CONTROL, COLD and HOT drink conditions was, 1.54 ± 0.3 L, 1.63 ± 0.3 L and 1.59 ± 0.2 L, respectively and was not different between conditions ($F_{(2,18)} = .592$, $p = .564$, $\eta p^2 = .050$). The volume of sweat evaporated was 1.46 ± 0.4 L, 1.52 ± 0.3 L and 1.49 ± 0.2 L, respectively and was not different between condition ($F_{(2,18)} = .214$, $p = .809$, $\eta p^2 = .054$). This equated to 95 ± 13 %, 94 ± 6 % and 94 ± 7 % of sweat being evaporated.

*Regional Sweat Production – Sweat Pad collection at the Subscapular and Forearm*

Regional sweat production increased as the trial ensued (subscapular: main effect for time: $F_{(3,27)} = 39.574$, $p = .001$, $\eta p^2 = .815$; forearm: main effect for time: $F_{(3,27)} = 59.568$, $p = .010$, $\eta p^2 = .869$). The sweat production seen at the forearm plateaued after the first sweat pad collection whereas sweat volume continued to increase at the subscapular region until the final measurement point. Yet, there were no differences in regional sweat production overall (no main effect for condition: subscapular: $F_{(2,18)} = 1.880$, $p = .181$, $\eta p^2 = .173$; forearm: $F_{(2,18)} = 1.561$, $p = .237$, $\eta p^2 = .148$) or interaction effects (subscapular: $F_{(6,54)} = .513$, $p = .796$, $\eta p^2 = .054$; forearm: $F_{(6,54)} = .738$, $p = .622$, $\eta p^2 = .076$). Subscapular and forearm local sweat rates,

converted to $g.hr^{-1}$, after each drink are presented in figure 2. The mean sweat rate across the CONTROL, COLD and HOT drink conditions at the subscapular were 1.784 ± 0.673 $g.hr^{-1}$, 2.072 ± 1.066 $g.hr^{-1}$, and 1.811 ± 0.749 $g.hr^{-1}$. Sweat rates at the forearm were of a similar magnitude; data not shown.

***INSERT FIGURE 2 NEAR HERE***

*Galvanic Skin Conductance*

GSC response at the bicep and subscapular region are displayed in figure 3A. The extent of GSC was significantly greater (t = -6.675, p = .001) at the subscapular region (grand mean ± SD; 21.5 ± 3.6 $\mu$S) compared to the bicep region (12.8 ± 4.2 $\mu$S) indicating greater proximal sweating irrespective of the test condition. When the change in GSC was examined immediately after drink ingestion (i.e. in the following 3-minutes) it was 0.20 ± 0.8 $\mu$S, −0.20 ± 1.74 $\mu$S, and 0.30 ± 2.2 $\mu$S in the CONTROL, COLD and HOT drink conditions, respectively at the bicep and 2.2 ± 2. $\mu$S, 2.2 ± 2.0 $\mu$S, 1.3 ± 2.2 $\mu$S at the subscapular region. There was no statistical evidence that the rate of sweating was altered at either site (bicep: $F_{(2,18)}$ = .182, p = .835, $\eta p^2$ = .020; subscapular: $F_{(2,18)}$ = .469, p = .663, $\eta p^2$ = .050) despite visual evidence of GSC being consistently lower in the COLD drink condition at the bicep (figure 3B) and a sinusoidal wave after each hot drink ingestion at the subscapular region (figure 3A).

***INSERT FIGURE 3 NEAR HERE***

364 *Perceptual Responses*

365 *Thermal sensation*

366 Participant's reported a similar TS at the start of each trial corresponding to the worded
367 descriptor *Slightly warm*. As the trial ensued the participant's TS increased steadily (main
368 effect for time: $F_{(10,90)} = 28.702$, $p = .001$, $\eta p^2 = .761$) and reached a descriptive sensation of
369 *Hot* at the end of the FI period (grand mean ± SD: 17.3 ± 1.5 cm) and peaked at being *Very*
370 *hot* by the end of the TTE (grand mean ± SD: 18.7 ± 1.2 cm) yet this did not happen to any
371 differing extent in either condition (no main effect for condition: $F_{(2,18)} = 1.065$, $p = .365$, $\eta p^2$
372 $= .106$) or produce an interaction effect ($F_{(20,180)} = 11.917$, $p = .160$, $\eta p^2 = .163$). TS data are
373 shown in figure 4A.

374

375 ***INSERT FIGURE 4 NEAR HERE***

376

377 *Thermal Comfort*

378 Participant's reported a similar TC at the start of each trial in each condition which
379 corresponded to the worded descriptor *Just comfortable* to *Comfortable*. As the trial ensued
380 the participant's TC decreased steadily (main effect for time: $F_{(10,90)} = 38.693$, $p = .001$, $\eta p^2 =$
381 $.811$) and reached a descriptive sensation of approaching *Uncomfortable* at the end of the FI
382 period (grand mean ± SD: 6.6 ± 4.3 cm) and peaked at being more *Uncomfortable* by the end
383 of the TTE (grand mean ± SD: 3.9 ± 3.4 cm). Participants felt less thermal discomfort (main
384 effect for condition: $F_{(2,18)} = 3.915$, $p = .039$, $\eta p^2 = .303$) in the COLD drink condition than
385 the CONTROL condition ($p = .025$) and approached being different to the HOT drink
386 condition ($p = .077$). The CONTROL condition and the HOT drink trial were not different ($p$
387 $= .889$). An interaction effect was also evident ($F_{(20,180)} = 6.030$, $p = .002$, $\eta p^2 = .202$) where

consistent differences were seen between the COLD drink condition and the CONTROL; time point differences are shown in figure 4B.

*Gut Comfort*

All participants rated their GC as *Very comfortable* before the trial commenced. As the trial ensued GC rating increased indicating greater discomfort (main effect for time: $F_{(10,90)}$ = 6.078, p = .012, $\eta p^2$ = 403). GC tended to be worst in the HOT drink trial (2 ± 0.3) followed by the COLD drink (2 ± 0.4) and then the CONTROL condition (1 ± 0.2) although this did not culminate in any differences between conditions (no main effect for condition: $F_{(2,18)}$ = 3.078, p = .071, $\eta p^2$ = .255) or an interaction effect ($F_{(20,18)}$ = 1.221, p = .241, $\eta p^2$ = .119). It is important to note that, despite some inter-individual variation in the GC responses, the mean responses never exceed a rating of 2 corresponding to *Comfortable*; see figure 4C.

*Skin Wetness*

Despite the dry ambient conditions and convective airflow provided by the fan, as the trial ensued and the participants started to sweat their sensation of SkW increased (main effect for time: $F_{(10,90)}$ = 67.086, p = .001, $\eta p^2$ = .882). At the end of the FI period SkW was rated as *Sweat/water runs somewhere off* (grand mean ± SD: 7 ± 1) and reached the descriptive rating *Sweat water runs of many places* (8 ± 1). There were no differences between conditions (no main effect for condition: $F_{(2,18)}$ = .249, p = .782, $\eta p^2$ = .027) or an interaction effect ($F_{(20,18)}$ = 1.555, p = .068, $\eta p^2$ = .147). SkW responses are shown in figure 4D.

*RPE and Heart Rate*

Mean ± SD RPE response is displayed in figure 5A. Shortly after the commencement of exercise the participant's RPE increased corresponding with the worded descriptor *Light* (grand mean 11 ± 2). Despite no change in exercise intensity RPE increased significantly throughout the FI exercise period and was 15 ± 3 at the end of this part of the protocol (main effect for time: $F_{(7,63)} = 59.503$, $p = .001$, $\eta p^2 = .905$). At the end of the TTE RPE was 19 ± 1 corresponding to the worded descriptor *Maximal exertion* but there were no significant differences in any of the conditions (no main effect: $F_{(2,18)} = .808$, $p = .461$, $\eta p^2 = .082$) or interaction effects: $F_{(14,126)} = 1.497$, $p = .121$, $\eta p^2 = .143$).

***INSERT FIGURE 5 NEAR HERE***

Mean ± SD HR response is displayed in figure 5B. Heart rate did not reflect the RPE responses and a showed a steady increase (main effect for time: $F_{(7,63)} = 59.503$, $p = .001$, $\eta p^2 = .869$) as the fixed exercise period ensued (grand mean at the end of fixed exercise: 163 ± 14 $b.min^{-1}$). Overall HR was significantly higher in the CONTROL condition (main effect for condition: $F_{(2,18)} = 3.553$, $p = .050$, $\eta p^2 = .283$) than the COLD drink ($p = .039$) but only approached being different to the HOT drink trial ($p = .052$). The two drink conditions were not different to one another ($p = .464$) and there was no interaction effect ($F_{(14,126)} = 1.260$, $p = .242$, $\eta p^2 = .123$).

## Discussion

This study examined whether the ingestion of a hot drink (i.e. 50°C) is beneficial to thermoregulation at rest and during exercise in hot conditions when evaporation was enabled (i.e. a dry environment) in contrast to a cold drink (i.e. 5°C) and a no-drink control. The perceptual, thermoregulatory and performance implications of these differing drink temperatures were considered with a view to informing fluid replacement guidelines. A conflicting behavioural (i.e. perceptual) and thermoregulatory effect (i.e. altered sweat production) was plausible since it is possible that a hot drink could increase thermal discomfort through increases in temperature sensation by stimulation of the gut but actually *improve* body temperature regulation by elevating sweat production (Bain et al. 2012). Although highly theoretical, this in turn could have had the potential to reduce surface and eventually internal body temperature. However, this would also have increased the rate at which dehydration developed that could be a problem in situations where water provision is limited and may only be evident over an extended period of time. Yet, we found no change in the rate of sweating or the extent of dehydration after hot drink ingestion; thus, $H_1$ for the hot drink was not supported.

By contrast, an opposing effect on sweating was possible when a cold drink was ingested. A cold drink could have reduced sweat production through direct stimulation of a gut thermoreceptor which has been confirmed as being present in mammals and humans (Bain et al. 2012; Morris et al. 2014 & 2017; Nadel et al. 1970; Rawson & Quick, 1972). There was only visual evidence for a reduction in peripheral sweating (i.e. bicep GSC) following cold drink ingestion but a significant reflex reduction in $T_{msk}$ immediately after cold drink ingestion. Yet these changes were small, periodic and beyond the detection resolution of the previously validated (Morris et al. 2013) sweat pad collection technique that has been shown

to be sensitive to change with similar protocols (Morris et al. 2013). However, it must be noted that a longer collection period may have yielded different results. Nevertheless, our use of the GSC as an index of change in sweat rate, which extends its use beyond that of sweat ion reabsorption (Amano et al. 2016), shows promise. Indeed, the GSC data showed a significant regional difference in sweat rate and descriptive changes in response to both hot and cold drinks. Our use of GSC in this way is novel but requires further scrutiny.

The effects of the ingestion of these different temperature drinks on thermal comfort were potentially complicated and could have been confounded by changes in palm temperature without appropriate control. We were careful to avoid this methodological limitation and the resultant effect was that the cold drink improves thermal comfort in a consistent manner towards the end of the trial (see figure 4B) by contrast to the transient alterations in skin temperature and sweating that we saw. Accordingly, we hypothesise a thermal signalling role for the gut thermoreceptor in producing perceptions of thermal comfort but not thermal sensation that extend beyond the reflex physiological response. The opposing effect was not evident following hot drink ingestion. Collectively we suggest the high ambient temperatures and exercise work rates were salient in producing the thermal comfort vote in the early part of trial; therefore we only partially support $H_2$. The role of the gut only became salient towards in the second half of the trial where relief of thermal discomfort after cold drink ingestion rather than its acceleration after hot drink ingestion was only seen (see figure 4B). Given that the experience of thermal discomfort is a driver of behvioural thermoregulation (Taylor et al. 1995) it may be that this proves to be ergogenic as has been seen in other studies (e.g. Lee et al. 2008b; Mundel et al. 2006) albeit with less realistic fluid consumption volumes and profiles. From a mechanistic perspective, we suggest a reciprocal role for the gut along with visceral thermoreceptors in contributing to thermoreception that may only be salient after skin

temperature has plateaud (at >34°C in the present study; see also Nadel et al. 1970) and deep body temperature has risen (i.e. >37.8°C) which approximately coincides with the ingestion of the second cold drink in the present study (see figures 1A & 1B). At rest and during lower intensity exercise, beverage temperature has been shown to influence sudomotor responses relatively independently (Bain et al. 2012; Morris et al. 2014 & 2017). We suggest that less independence may be seen when internal and peripheral temperatures are raised although it is also possible that the sweat response would be changed in response to drink temperature outside of the thermal range of skin and rectal temperatures we saw in the present study.

These data have clear implications for fluid replacement guidelines. We show, through consistent evidence of a greater thermal strain (i.e. higher $T_{rec}$ and HR; see figures 1A & 5B) and greater post trial dehydration (2.1 ± 0.3% body mass loss) in the control condition, that failing to ingest fluid to replace that lost to sweat will increase the risk of dehydration and heat-illness; this agrees with many other studies (e.g. Casa et al. 2000; Galloway & Maughan, 2000). The temperature of that fluid, in the small volumes consumed in the present study, is less important as the consequent effect on the thermoregulatory responses was negligible. It is probable that the associated change in gastric temperature following hot or cold drink ingestion was only transient (Shi et al. 2000) thereby reflecting the thermoregulatory response we see here. Larger volumes of hot or cold fluid may sit in the gut and result in a more pronounced thermoregulatory change (e.g. Lee et al. 2008b) and an *ad libitum* consumption profile may have resulted in more fluid being consumed (e.g. Mündel et al. 2006). Given the choice, the vast majority of persons would select a cool drink to alleviate the thermal burden from a perceptual and physiological perspective (Barwood, 2012) and we find no refuting evidence to counter this idea when fluid consumption profile keeps hydration status within a 1% limit. Indeed, a cold drink has the potential to alleviate thermal discomfort to a greater

extent than not drinking or compared to a hot drink (see figure 4B) although we were not aware of any individual preference for cold over hot fluid. Nevertheless, it is probable that the hedonic tone of the cold drink when consumed in the hot environment is central to this result (Szylyk et al. 1989).

We also make the important addition of a valid exercise performance measure following hot and cold drink ingestion by contrast to the no drink control; previous studies have primarily focussed on cold drink ingestion. The magnitude of performance difference between ingesting (i.e. hot or cold drink) and failing to ingest any fluid (i.e. the control) was approximately 54%; $H_3$ is rejected. The extent of dehydration estimated by body mass loss was roughly half in the drink trials (COLD drink: 0.9 ± 0.3%; HOT drink: 0.9 ± 0.4%) of that seen in the control trial (i.e. 2.1 ± 0.3%). The approximate 1.2% difference is implicated in the higher thermal strain and poor performance that was seen in the control condition. These data also suggest that we were able to achieve fluid replacement levels that are in line with the ACSM fluid replacement guidelines (ACSM et al. 2007) and demonstrate that we achieved a realistic, and therefore valid, fluid consumption profile. Indeed, the extent of dehydration did not exceed the threshold for measured body mass loss (i.e. approximately 2%) which correlates with the increase in plasma osmolality (Cheuvront and Kenefick, 2014) and is suggested to drive the thirst response. Hence a "no drink" condition was a plausible control. The drink conditions were carefully titrated to avoid hyper or hypohydration and met the sweating requirements of the ambient conditions to reduce dehydration to 1%. .

**Conclusions and Recommendations**

The present study suggests that there is no negative thermoregulatory or performance effect associated with ingesting hot or cold drinks when exercise is performed in a hot, dry

environment. Indeed, both drinks sustained performance to a similar magnitude compared to a no drink control. There is some tentative evidence that cold drinks may enhance thermal comfort beyond the resultant physiological response of transient reductions in $T_{msk}$ and peripheral sweating that were seen here. Potentially, thermoreceptor signals from the gut become more salient as thermal profile approaches becoming hyperthermic but are not accelerated when hot fluid is ingested. It is clear that it is critical that at least some fluid is ingested to offset dehydration.

## Acknowledgements

This work was funded by a research grant from the European Hydration Institute

There are no conflicts of interest to declare.

## References


1. Armstrong LE, Johnson EC, Kunces LJ, Ganio MS, Judelson DA, Kupchak BR et al (2014) Drinking to thirst versus drinking ad libitum during road cycling. Int J Athl Train 49(5):624-631. doi: 10.4085/1062-6050-49.3.85.
2. Amano T, Gerrett N, Inoue Y, Nishiyasu T, Havenith G Kondo N (2016) Determination of the maximum rate of eccrine sweat glands' ion reabsorption using the galvanic skin conductance to local sweat rate relationship. Eur J Appl Physiol. 116(2): 281-290. doi: 10.1007/s00421-015-3275-9.
3. American College of Sports Medicine, Sawka MN, Burke LM, Eichner ER, Maaughan RJ, Montain SJ et al (2007) American College of Sports Medicine position stand: exercise and fluid replacement. Med Sci Sports Exerc. 39(2):377–390. doi: 10.1249/mss.0b013e31802ca597.
4. Bain AR, Lesperance NC, Jay O (2012) Body heat storage during physical activity is lower with hot fluid ingestion under conditions that permit full evaporation. Acta Physiol Scand. 206 (2): 98-108. doi: 10.1111/j.1748-1716.2012.02452.x.
5. Barwood MJ. Hot drinks all round (2012) Acta Physiol Scand. 206: 94-95. doi: 10.1111/j.1748-1716.2012.02458.x
6. Borg GAV. Psychophysical basis of physical exertion (1982) Med Sci Sports Exerc. 14:377-381.
7. Burdon CA, O'Connor HT, Gifford JA, Shirreffs SM, Chapman P, Johnson N (2010) Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. J Sport Sci. 28(11):1147-1156. doi: 10.1080/02640414.2010.489197.

8. Burdon CA, O'Connor HT, Gifford JA, Shirreffs SM (2010) Influence of beverage temperature on exercise performance in the heat: a systematic review. Int J Sport Nutr Exerc Metab. 20(2):166-174. doi:10.1123/ijsnem.20.2.166
9. Casa DJ, Maresh CM, Armstrong LE, Kavouras SA, Herrera JA, Hacker FT (2000) Intravenous versus oral rehydration during a brief period: responses to subsequent exercise in the heat. Med Sci Sports Exerc. 32(1):124-33. doi: 10.1097/00005768-199805001-01889.
10. Cheuvront SN, Kenefick RW (2014) Dehydration: physiology, assessment, and performance effects. Comp Physiol. 4:257–285. doi: 10.1002/cphy.c130017.
11. DuBois D, DuBois EF (1915) The measurement of the surface area of man. Int Arch Med. 15:868-81.
12. Galloway S, Maughan R (2000) The effects of substrate and fluid provision on thermoregulatory and metabolic responses to prolonged exercise in a hot environment. J Sport Sci. 18:339-351. doi: 10.1080/026404100402403
13. Gonzalez JT, Fuchs CJ, Smith FE, Thelwall PE, Taylor R, Stevenson EJ, et al (2015) Ingestion of glucose or sucrose prevents liver but not muscle glycogen depletion during prolonged endurance-type exercise in trained cyclists. Am J Physiol: End Metab. 309: E1032-E1039. https://doi.org/10.1152/ajpendo.00376.2015
14. Hensel H, Schafer K (1984) Thermoreception and temperature regulation in man. In: Ring EFJ, Phillips B (eds) Recent advances in medical thermology. Plenum Press, New York pp. 51-64.
15. Hew-Butler T, Verbalis JG, Noakes TD (2006) International Marathon Medical Directors Association. Updated fluid recommendation: position statement from the International Marathon Medical Directors Association (IMMDA). Clin J Sport Med. 16(4): 283–292.

16. Lamarche DT, Meade RD, McGinn R, Poirier MP, Friesen, BJ, Kenney, GP (2015) Temperature of ingested water during exercise does not affect body heat storage. Med Sci Sports Exerc. 2015;47(6):1272-1280. doi: 10.1249/MSS.0000000000000533
17. Lee JK, Maughan RJ, Shirreffs SM (2008a) The influence of serial feeding of drinks at different temperatures on thermoregulatory responses during cycling. J Sport Sci. 26(6):583-590. doi: 10.1080/02640410701697388
18. Lee JK, Shirreffs SM, Maughan RJ (2008b) Cold drink ingestion improves exercise endurance capacity in the heat. Med Sci Sports Exerc. 40:1637–1644. doi 10.1249/MSS.0b013e318178465d
19. Lee JK, Shirreffs SM (2007) The influence of drink temperature on thermoregulatory responses during prolonged exercise in a moderate environment. J Sport Sci. 25(9):975-985. doi: 10.1080/02640410600959947
20. Morris NB, Bain AR, Cramer MN. Jay O (2014) Evidence that transient changes in sudomotor output with cold and warm fluid ingestion are independently modulated by abdominal, but not oral thermoreceptors. J Appl Physiol. 116(8):1088-1095. Doi: 10.1152/japplphysiol.01059.2013
21. Morris NB, Cramer MN, Hodder SG, Havenith G, Jay O (2013) A comparison between the technical absorbent and ventilated capsule methods for measuring local sweat rate. J Appl Physiol. 114(6):816-823. Doi: 10.1152/japplphysiol.01088.2012
22. Morris NB, Filingeri D, Halaki M, Jay O (2017) Evidence of viscerally-mediated cold defence thermoeffector responses in man. J Physiol. 595(4): 1202-1204. Doi: 10.1113/JP273052
23. MÜndel T, King J, Collacott E, Jones DA (2006) Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. Exp Physiol. 91(5):925-933. Doi: 10.1113/expphysiol.2006.034223

24. Nadel ER, Horvath SM, Dawson CA, Tucker A (1970) Sensitivity to central and peripheral thermal stimulation in man. J Appl Physiol 29: 603-609.
25. Noakes TD (2011) Changes in body mass alone explain almost all of the variance in the serum sodium concentrations during prolonged exercise. Has commercial influence impeded scientific endeavour? Br J Sports Med. 45(11):475–7. Doi: 10.1136/bjsm.2010.075697
26. Olesen BW (1980) How many sites are necessary to estimate a mean skin temperature? In: Hales JRS (ed) Thermal Physiology. Raven Press: New York, pp. 33-38.
27. Rawson RO, Quick KP (1972) Localization of intra-abdominal thermoreceptors in the ewe. J Physiol. 222:665–667.
28. Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal stress. Physiol Rev. 54:75–159.
29. Rowell LB, Marx HJ, Bruce RA, Conn RD, Kusumi, F (1966) Reductions in cardiac output, central blood volume, and stroke volume with thermal stress in normal men during exercise. J Clin Invest. 45:1801-1806.
30. Shi X, Bartoli W, Horn M, Murray R (2000) Gastric emptying of cold beverages in humans: effect of transportable carbohydrates. Int J Sport Nutr Exerc Metab. 10(4):394-403. https://doi.org/10.1123/ijsnem.10.4.394
31. Smith CJ, Johnson JM (2016) Responses to hyperthermia. Optimizing heat dissipation by convection and evaporation: neural control of skin blood flow and sweating in humans. Auton Neuroscience: Basic Clin. 196:25-36. Doi: 10.1016/j.autneu.2016.01.002
32. Smith CJ, Kenney WL, Alexander LM (2013) Regional relation between skin blood flow and sweating to passive heating and local administration of acetylcholine in

young, healthy humans. Am J Physiol Regul Integr Comp Physiol. 304:R566-R573. Doi: 10.1152/ajpregu.00514.2012

33. Storaas G, Bakkevig MK (1996) Correlation between measured skin wettedness and subjective sensations of skin wetness. In: Shaprio Y, Moran DS, Epstein Y. The Proceedings of the 7th International Conference on Environmental Ergonomics (ICEE). Freund Publishing House, Tel Aviv, Israel, pp 131–134.

34. Szlyk PC, Sils IV, Francesconi RP, Hubbard RW, Armstrong LE (1989) Effects of water temperature and flavouring on voluntary dehydration in men Physiol Behav. 45:639-647. https://doi.org/10.1016/0031-9384(89)90085-1

35. Taylor NA, Allsopp NK, Parkes DG (1995) Preferred room temperature of young versus aged males: the influence of thermal sensation, thermal comfort, and affect. J Gerontol A Biol Sci Med Sci. 50:M216–M221. Doi: 10.1093/gerona/50A.4.M216

36. Zhang H (2003) Human thermal sensation and comfort in transient and non- uniform thermal environments. PhD thesis. Berkeley: University of California. doi: https://escholarship.org/uc/item/11m0n1wt

659 **Figure Legends**

660 Figure 1 A-B. Mean ± SD $T_{rec}$, and $T_{msk}$ responses after each drink ingestion (condition
661 dependent) during rest, fixed intensity exercise (55% $P_{Max}$) and TTE end after 80% $P_{Max}$
662 cycling; main effects for condition are indicated on each panel where applicable; n = 10.

663 Figure 2 A-B. Mean ± SD local sweat rate at the subscapular and forearm regions after each
664 drink (condition dependent) during rest, fixed intensity exercise (55% $P_{Max}$) and TTE end
665 after 80% $P_{Max}$; n=10.

666 Figure 3 A-B. Mean GSC at the subscapular and forearm regions after each drink (condition
667 dependent) during rest and fixed intensity exercise (55% $P_{Max}$), SD data are omitted for
668 clarity; n=10.

669 Figure 4 A-D. Mean ± SD TS, TC, GC and SkW after each drink during rest, fixed
670 intensityexercise (55% $P_{Max}$) and TTE end after 80% $P_{Max}$. Main effects for conditions are
671 indicated on each panel where applicable, brackets indicate near significance and * indicate
672 time point specific differences; n=10.

673 Figure 5 A-B. Mean ± SD RPE and HR responses after each drink during rest, fixed intensity
674 exercise (55% $P_{Max}$) and TTE end after 80% $P_{Max}$. HR data are displayed to corresponding
675 time points for RPE; main effects for condition are indicated on each panel where applicable;
676 n=10.